

# Neutrino detectors for future experiments

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We review detector technologies which are currently considered for ultimate nucleon decay searches, new generation astrophysical neutrinos studies, and for future long-baseline neutrino experiments at new high-intensity neutrino beam facilities. We focus our discussion on Phase-II experiments with a timescale of  $10 \simeq 20$  years. We point out that there are very few detector technologies which are general purpose and versatile enough in order to potentially address non-accelerator based physics and a large variety of future neutrino beam types ranging from superbeams, betabeams and neutrino factories from subGeV to 10's GeV energies.

## 1. NEW GENERATION DETECTORS

It is expected that new neutrino facilities will provide new opportunities to further develop neutrino physics, especially when coupled to long baselines.

The current round of long baseline experiments ("phase-0") are meant to confirm the neutrino oscillation effect found in atmospheric neutrinos. K2K[1], MINOS[2], OPERA[3] and ICARUS[4] belong to this generation.

After that, the focus will shift towards second generation experiments ("phase-I") designed and optimized to detect the subleading  $\nu_\mu \rightarrow \nu_e$  atmospheric oscillations. The T2K experiment in Japan is the only approved project, with its beamline under construction and commissioning planned for  $\simeq 2009$ . The T2K beam is expected to reach a proton intensity of 0.75 MW around 2011 and could be upgraded to 4 MW by increasing the repetition rate of the 50 GeV synchrotron at J-PARC, eliminating idle time in the acceleration cycle and by doubling the number of circulating protons[5]. The target region is however a critical item for the high intensity. The far detector is SuperKamiokande. T2K should measure  $\nu_\mu \rightarrow \nu_\mu$  with  $\delta(\Delta m_{23}^2) \approx 10^{-4} eV^2$  and  $\delta(\sin^2 \theta_{23}) \approx 0.01$ . It will find evidence for  $\nu_\mu \rightarrow \nu_e$  if  $\sin^2 2\theta_{13} > 0.006$ .

With Phase 0&1 experiments on their way, one must consider possible "phase-II" projects in  $10 \simeq 20$  years (?), able to address more aspects of the phenomenology of neutrino oscillations, beyond those addressed by the currently approved experiments. For example:

1. Study precisely the  $L/E$  dependence of the oscillation probability;
2. Improve errors to  $\delta(\Delta m_{23}^2) \approx 1\%$ ;
3. Improve errors to  $\delta(\sin^2 \theta_{23}) < 1\%$ ;
4. Improve sensitivity to  $\sin^2 2\theta_{13}$  by a factor  $\times 5$  or  $\times 10$  w.r.t. to T2K or precisely measure it if T2K has found a signal;
5. Find evidence for CPV ( $\delta \neq 0$ );
6. Fix the sign of  $\Delta m_{23}^2$  and study matter effects;
7. Observe  $(\Delta m_{21}^2, \sin^2 \theta_{12})$  oscillations in terrestrial experiments;
8. Over-constrain the  $U_{PMNS}$  matrix (unitarity tests);
9. Search for non-standard interactions;
10. Any other business.

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Table 1

Quick comparison of detector technologies for future experiments. Solar means solar neutrinos. SN means supernovae neutrinos (burst + relic). Atm means atmospheric neutrinos.

Detector	Mass kt	Solar	SN	Atm	Nucleon decay	Superbeam, $\beta$ -beam			$\nu$ -factory
						subGeV	GeV	10's GeV	10's GeV
WC	$\simeq 1000$	$\approx$	yes	yes	yes	yes	$\approx$	no	no
LAr	$\simeq 100$	yes	yes	yes	yes	yes	yes	yes	yes ( $\mu$ -catcher)
Magnetized LAr	$\simeq 25$	yes	yes	yes	yes	yes	yes	yes	$e^\pm, \mu^\pm$
Magnetized sampling Cal.	$\simeq 50$	no	no	$\mu^\pm$	no	$\approx$	yes	yes	$\mu^\pm$
Non-magnetized sampling Cal.	$\simeq 50$	no	no	$\mu$ 's	no	$\approx$	yes	yes	no
Emulsion hybrid	$\simeq 1$	no	no	no	no	no	$\approx$	yes	$\tau^\pm$

For the search for CP violation in the lepton sector and/or the determination of the mass hierarchy, the discovery of a non-vanishing  $\theta_{13}$  via the subleading  $\nu_\mu \rightarrow \nu_e$  oscillation in the Phase-I is a prerequisite. Otherwise, the Phase-II is designed exclusively to improve the sensitivity to  $\nu_\mu \rightarrow \nu_e$  oscillations with little other prospects. Note that for  $\sin^2 2\theta_{13} < \simeq 0.001$ , a non-negligible amount of  $\nu_\mu \rightarrow \nu_e$  transitions are induced by the solar parameters ( $\Delta m_{12}^2$ ,  $\theta_{12}$ ) hence energy dependent studies of the oscillation probability will be mandatory to disentangle the 1 – 2 and 1 – 3-driven effects.

Since not all parameters relevant for the physics of Phase-II are known (e.g.  $\theta_{13}$ ), we should tend towards a general purpose and versatile detector that gives us the largest opportunity to perform interesting and new physics in the year  $\simeq 2020$ , whatever that physics will be. It appears that such a detector should possess the following attributes:

1. Should be very massive & general purpose, and not solely “tuned” to a given physics topic which might be relevant today, but not necessarily tomorrow;
2. Should detect a wide range of energies and have the proper energy resolution to “see the oscillations”, measure the oscillations parameters precisely and disentangle possible degeneracy;

3. Should have the granularity to potentially address all the existing  $e/\mu/\tau$  flavors in the final states;
4. Should have a clean NC, CC separation and good background suppression;
5. Should address both accelerator & non-accelerator physics, hence be located underground (depth to be optimized);
6. Should be ready to find the unexpected (many years will pass from design to data taking);
7. Should be cost effective.

It is also clear that one needs to consider the complete system including detector, accelerator complex and beam type simultaneously, and systematically optimize the energies, baselines, intensities, ... This challenging task has not been yet fully completed given the size of the parameter space. It is important to pursue such optimizations (“feasibility studies”) before embarking on a specific road for Phase-II projects.

We believe that new experiments of the envisaged scale must address a wide non-accelerator physics program as well as, either independently while waiting to be coupled to a Phase-II neutrino facility, or simultaneously performing accelerator and non-accelerator physics programs. Hence, it is important to develop new massive underground

detectors for astrophysical neutrinos and nucleon decay searches, while keeping the possibility open of a future neutrino facility directed towards it. In general, laboratories planning new accelerator developments and/or upgrades should keep in mind possible neutrino physics.

A comparison of possible detector technologies is summarized in Table 1, organized according to their types and desired masses. We consider Water Cerenkov detectors (WC) at the megaton-scale, liquid Argon TPC's without and with magnetic field (LAr), fine sampling calorimeters with and without magnetic field, and emulsion hybrid detectors. The 3th to 6th columns illustrate the potentialities to address the non-accelerator physics program (solar, supernova, atmospheric neutrinos and nucleon decay searches). The last columns illustrate the capability to study artificial neutrino beams like Superbeam or Betabeams of various energies (subGeV, GeV and 10's GeV) and the neutrino factory (assumed to have 10's GeV energy).

The various detector technologies are discussed in more details in the following sections.

## 2. WATER CERENKOV DETECTORS

Two generations of large water Cerenkov detectors at Kamioka (Kamiokande[6] and Superkamiokande[7]) have been very successful in research of neutrino physics with astrophysical sources. In addition, the first long baseline neutrino oscillation experiment with accelerator-produced neutrinos, K2K, has been conducted with Superkamiokande as far detector.

Superkamiokande is composed of a tank of 50 kton of water (22.5 kton fiducial) which is surrounded by 11146 20-inch phototubes immersed in the water. About  $170 \gamma/cm$  are produced by relativistic particles in water in the visible wavelength  $350 < \lambda < 500 \text{ nm}$ . With 40% PMT coverage and a quantum efficiency of 20%, this yields  $\approx 14$  photoelectrons per cm or  $\approx 7$  p.e. per MeV deposited.

There are good reasons to consider a third generation water Cerenkov detector with an order of magnitude larger mass than Superkamiokande: Hyperkamiokande [8] (See Figure 1) has been pro-

posed with about 1 Mton, or about 20 times as large as Superkamiokande, based on a trade-off between physics reach and construction cost. Further scaling is limited by light propagation in water (scattering, absorption).

A megaton Water Cerenkov detector will have a broad physics programme, including both non-accelerator (proton decay, supernovae, ) and accelerator physics.

The concept of Hyper-Kamiokande was initially developed for nucleon decay searches. However, the possibility to use it as a far detector of a new high-intensity neutrino facility was considered to be an important purpose. Recently, the approval of the T2K project with a high intensity neutrino beam towards Superkamiokande has reopened the possibility to use HyperKamiokande as far detector to measure CP-violation in the leptonic sector. Indeed, with the 4 MW upgrade of the synchrotron and the 25 times larger fiducial mass, statistics at HK will be 100 times higher than at T2K-SK Phase-I.

Although this order of magnitude extrapolation in mass is often considered as straightforward, a number of R&D efforts including the site selection are needed before designing the real detector. At present, the following items are being studied: (i) site selection, (ii) cavity design and assessment, (iii) detector tank design and study of construction method, (iv) simulation studies of the detector performance for nucleon decay search and long baseline neutrino oscillation experiment, and (iv) development of HPDs (hybrid photo-detectors).

The Mozumi Mine, which is the current Superkamiokande site, cannot accomodate HyperK because there is no region of stable hard rock wide enough. Even if such a region existed, large-scale blasting for the excavation of a very big cavity should be avoided around Super-K which must stay in operation. A new site in Tochibora at a depth of 1400-1900 m.w.e. was found, which is located about 8 km south of the Mozumi Mine. This location allows for a solution to provide the T2K neutrino beam with the same spectral properties to both Super-K and Hyper-K.

The inner detector of Superkamiokande is instrumented with Hamamatsu 20-inch PMTs.

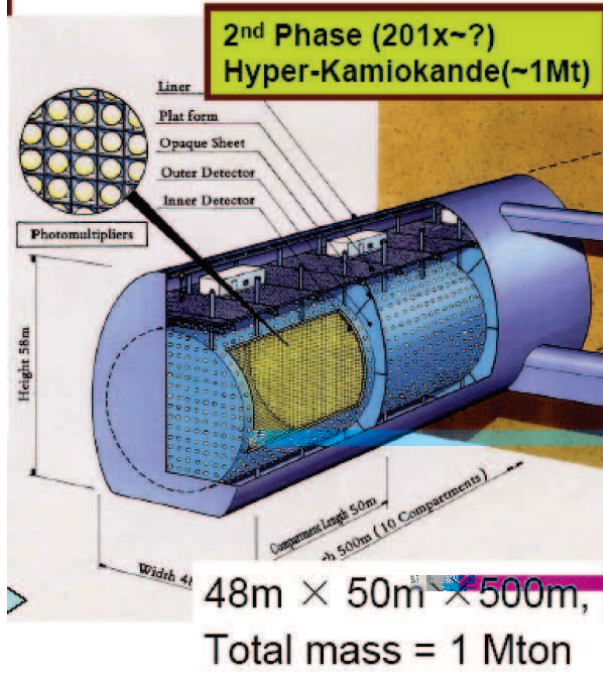


Figure 1. Possible configuration of the Hyper-Kamiokande detector.

An important item for Hyperkamiokande is developments of new photo-detectors: with the same photo-sensitive coverage as that of Superkamiokande ( $\approx 2\text{PMTs}/\text{m}^2$ ), the total number of PMTs needed for HyperK will be  $\approx 200'000$ . Possibilities to have devices with higher quantum efficiency, flat or thin and possibly operating in magnetic field are being pursued. Before the Superkamiokande accident, development of PMTs larger than 20 inch was seriously considered. However, R&D in this direction was reduced due to reasons of safety. Current efforts are focused on developments of large HPDs in collaboration with Hamamatsu. HPDs have a simpler structure than PMTs, which may allow for a pressure-tight spherical shape. Also, their production would be easier and cheaper than PMTs of similar size. Current goals are to reach 20-inch spherical HPDs. So far, 5-inch

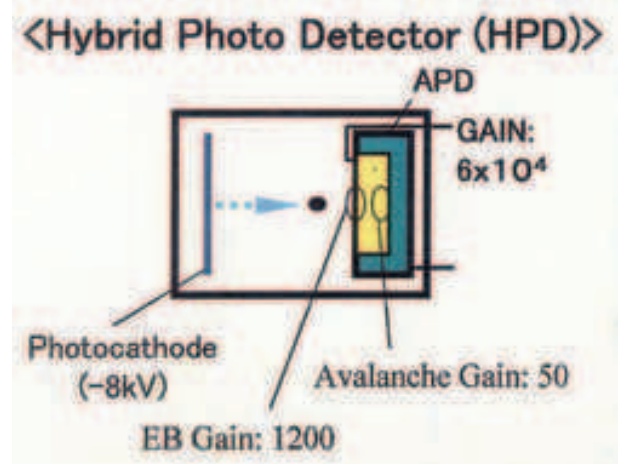


Figure 2. Schematic of a prototype 5-inch HPD.

HPDs (see Figure 2) have been prototyped and successfully tested. An avalanche gain of 50 and an electron bombarded gain of 1000 (3000) were obtained with HV at 8 kV (16 kV). Therefore, a total gain of  $5 \times 10^4$  was obtained at 8 kV. The next stage is the development of 13-inch HPDs.

Another option is the UNO detector[9] with the currently favored location at the Henderson mine (USA).

Finally a megaton detector has been proposed for the Fréjus tunnel in Europe.

### 3. LIQUID ARGON TIME PROJECTION CHAMBER

#### 3.1. The technique

Among the many ideas developed around the use of liquid noble gases, the Liquid Argon Time Projection Chamber [10] certainly represented one of the most challenging and appealing designs. The technology was proposed as a tool for uniform and high accuracy imaging of massive detector volumes. The operating principle of the LAr TPC was based on the fact that in highly purified LAr ionization tracks can be transported undistorted by a uniform electric field over distances of the order of meters [11]. Imaging is

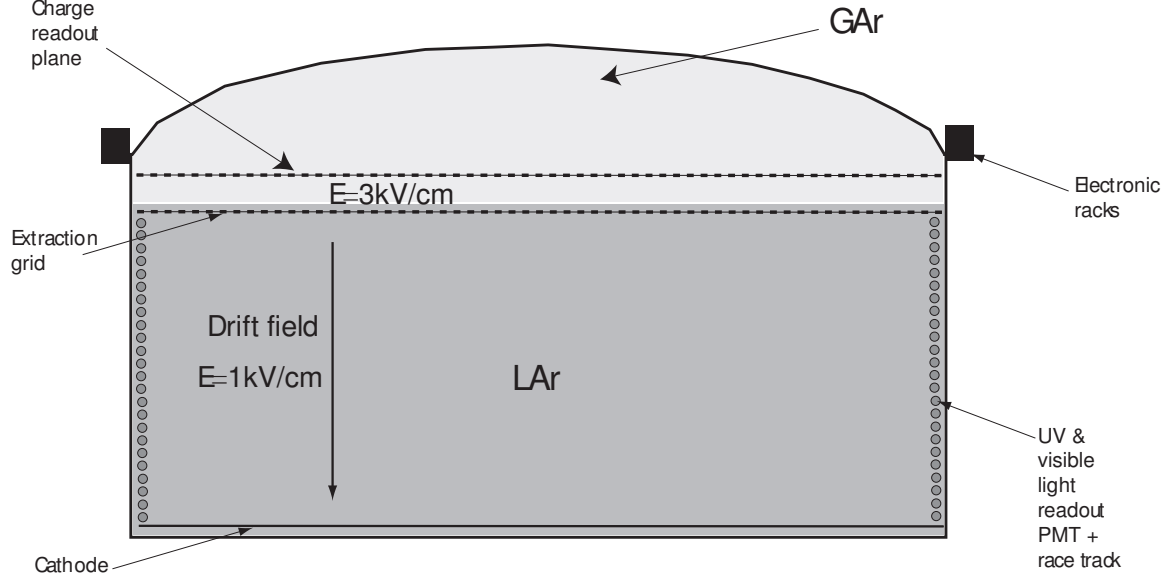


Figure 3. Schematic layout of a 100 kton liquid Argon detector. The race track is composed of a set of field shaping electrodes.

provided by wire planes placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons. Liquid Argon is an ideal medium since it provides high density, excellent properties (ionization, scintillation yields) and is intrinsically safe and cheap, and readily available anywhere as a standard by-product of the liquefaction of air.

The feasibility of this technology has been demonstrated by the extensive ICARUS R&D programme, which included studies on small LAr volumes about proof of principle, LAr purification methods, readout schemes and electronics, as well as studies with several prototypes of increasing mass on purification technology, collection of physics events, pattern recognition, long duration tests and readout. The largest of these devices had a mass of 3 tons of LAr [12,13] and has been continuously operated for more than four years, collecting a large sample of cosmic-ray and gamma-source events. Furthermore, a smaller device with 50 l of LAr [14] was exposed to the CERN neutrino beam, demonstrating the

high recognition capability of the technique for neutrino interaction events.

The largest liquid Argon TPC ever build so far is the ICARUS T600 detector, whose successful assembly culminated with its full test carried out at surface during the summer 2001 [15,16,17,18, 19,20]. Installation of this detector at the LNGS is ongoing and commissioning for data taking is expected in 2006.

A 100 kton liquid Argon TPC would deliver extraordinary physics output, owing to better event reconstruction capabilities provided by the LAr technique and would be one of the most advanced massive underground detectors built so far [21] with a rich astrophysical and accelerator based physics program: detection of supernova neutrinos[22], signal from relic supernova[23], oscillation physics at future neutrino beam facilities[24,25,26,27,28].

In order to reach the 10-100 kton mass adequate for a Phase-II, a new concept is required to extrapolate further the technology. Such a conceptual design is outline in the next section.

### 3.2. A conceptual design for a 100 kton detector

A conceptual design for a 100 kton LAr TPC was first given in Ref. [28] (See Figure 3). The basic design features of the detector can be summarized as follows: (1) Single 100 kton “boiling” cryogenic tanker at atmospheric pressure for a stable and safe equilibrium condition (temperature is constant while Argon is boiling). The evaporation rate is small (less than  $10^{-3}$  of the total volume per day given by the very favorable area to volume ratio) and is compensated by corresponding refilling of the evaporated Argon volume. (2) Charge imaging, scintillation and Cerenkov light readout for a complete (redundant) event reconstruction[28]. This represents a clear advantage over large mass, alternative detectors operating with only one of these readout modes. Scintillation and Cerenkov light can be readout essentially independently for improved physics performance[25]. (3) Charge amplification to allow for very long drift paths. The detector is running in bi-phase mode. In order to allow for drift lengths as long as  $\sim 20$  m, which provides an economical way to increase the volume of the detector with a constant number of channels, charge attenuation will occur along the drift due to attachment to the remnant impurities present in the LAr. This effect can be compensated with charge amplification near the anodes located in the gas phase.

The cryogenic features of the proposed design are based on the industrial know-how in the storage of liquefied natural gases (LNG,  $T \simeq 110$  K at 1 bar), which developed quite dramatically in the last decades, driven by the petrochemical and space rocket industries. LNG are used when volume is an issue, in particular, for storage. The technical problems associated to the design of large cryogenic tankers, their construction and safe operation have already been addressed and engineering problems have been solved by the petrochemical industry. The current state-of-the-art contemplates cryogenic tankers of 200000 m<sup>3</sup> and their number in the world is estimated to be  $\sim 2000$  with volumes larger than 30000 m<sup>3</sup> with the vast majority built during the last 40 years. Technodyne International Limited,

UK [29], which has expertise in the design of LNG tankers, has been appointed to initiate a feasibility study in order to understand and clarify the issues related to the operation of a large underground LAr detector. Their final report [30] demonstrates the technical feasibility and cost of this LAr tanker for physics experimentation.

A schematic layout of the inner detector is shown in Figure 3. The detector is characterized by the large fiducial volume of LAr included in a large tanker, with external dimensions of approximately 40 m in height and 70 m in diameter. A cathode located at the bottom of the inner tanker volume creates a drift electric field of the order of 1 kV/cm over a distance of about 20 m. In this field configuration ionization electrons are moving upwards while ions are going downward. The electric field is delimited on the sides of the tanker by a series of ring electrodes (race-tracks) placed at the appropriate potential by a voltage divider.

The tanker contains both liquid and gas Argon phases at equilibrium. Since purity is a concern for very long drifts of 20 m, we assume that the inner detector could be operated in bi-phase mode: drift electrons produced in the liquid phase are extracted from the liquid into the gas phase with the help of a suitable electric field and then amplified near the anodes. In order to amplify the extracted charge one can consider various options: amplification near thin readout wires, GEM [31] or LEM [32]. Studies that we are presently conducting show that gain factors of 100-1000 are achievable in pure Argon [33]. Amplification operates in proportional mode. Since the readout is limited to the top of the detector, it is practical to route cables out from the top of the dewar where electronics crates can be located around the dewar outer edges.

After a drift of 20 m at 1 kV/cm, the electron cloud diffusion reaches approximately a size of 3 mm, which corresponds to the envisaged readout pitch. Therefore, 20 m practically corresponds to the longest conceivable drift path. As mentioned above, drifting over such distances will be possible allowing for some charge attenuation due to attachment to impurities. If one assumes that the operating electron lifetime is at least  $\tau \simeq 2$  ms, one then expects an attenuation of a factor  $\sim 150$

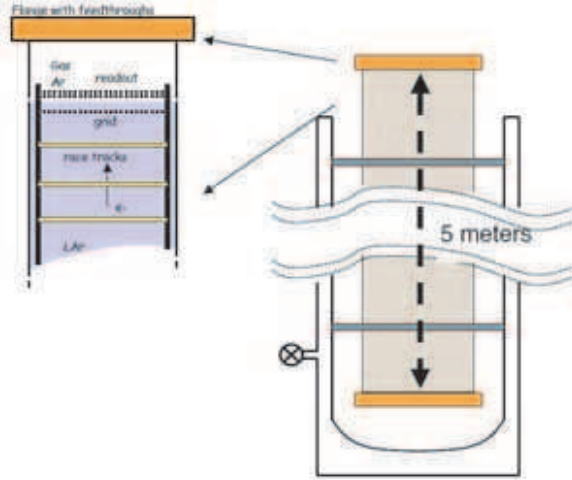


Figure 4. A 5 m long detector column is being realized as part of the R&D activity for very long drift paths with charge extraction and amplification.

over the distance of 20 m. This loss will be compensated by the proportional gain at the anodes. We remind that the expected attenuation factor (compensated by the amplification) will not introduce any detection inefficiency, given the value of  $\sim 6000$  ionization electrons per millimeter produced along a minimum ionizing track in LAr.

In addition to charge readout, one can envision to locate PMTs around the inner surface of the tank. Scintillation and Cerenkov light can be readout essentially independently. LAr is a very good scintillator with about  $50000 \gamma/\text{MeV}$  (at zero electric field). However, this light is essentially distributed around a line at  $\lambda = 128 \text{ nm}$  and, therefore, a PMT wavelength shifter (WLS) coating is required. Cerenkov light from penetrating muon tracks has been successfully detected in a LAr TPC [18]; this much weaker radiation (about  $700 \gamma/\text{MeV}$  between 160 nm and 600 nm for an ultrarelativistic muon) can be separately identified with PMTs without WLS coating, since their efficiency for the DUV light will be very small.

A series of R&D is ongoing to further develop the conceptual ideas outlined above, with the aim of identifying the main issues of the future systematic R&D and optimization activities[34]: (1) The study of suitable charge extraction, amplification and collection devices; (2) The understanding of charge collection under high pressure as expected for events occurring at the bottom of the large cryogenic tank; (3) The realization of a 5 m long detector column[34] (See Figure 4): We are constructing a column-like dewar 6 m long and 40 cm in diameter which will contain a 5 m long prototype LAr detector. The device will be operated with a reduced electric field value in order to simulate very long drift distances of up to about 20 m. Charge attenuation and amplification will be studied in detail together with the adoption of possible novel technological solutions. In particular, several options are being studied for both the HV field shaping electrodes and for the readout devices.

### 3.3. A magnetized liquid Argon TPC

The possibility to complement the LAr TPC with those provided by a magnetic field has been considered and would open new possibilities, important in the case of a neutrino factory[24,28]: (a) charge discrimination, (b) momentum measurement of particles escaping the detector (*e.g.* high energy muons), (c) very precise kinematics, since the measurements are multiple scattering dominated (*e.g.*  $\Delta p/p \simeq 4\%$  for a track length of  $L = 12 \text{ m}$  and a field of  $B = 1 \text{ T}$ ).

Unlike muons or hadrons, the early showering of electrons makes their charge identification difficult. The track length usable for charge discrimination is limited to a few radiation lengths after which the showers makes the recognition of the parent electron more difficult. In practice, charge discrimination is possible for high fields  $x = 1X_0 \rightarrow B > 0.5 \text{ T}$ ,  $x = 2X_0 \rightarrow B > 0.4 \text{ T}$ ,  $x = 3X_0 \rightarrow B > 0.3 \text{ T}$ . From simulations, we found that the determination of the charge of electrons of energy in the range between 1 and 5 GeV is feasible with good purity, provided the field has a strength in the range of 1 T. Preliminary estimates show that these electrons exhibit an average curvature sufficient to have electron charge

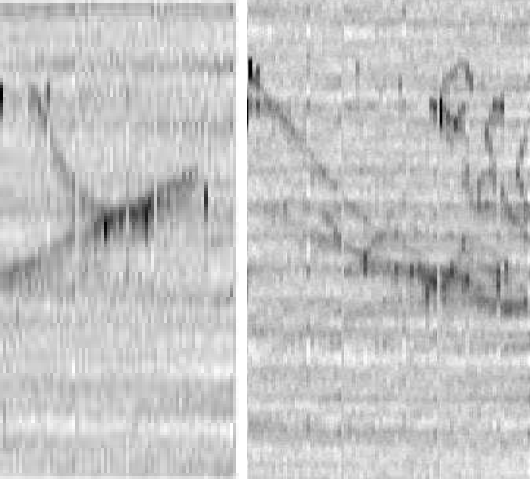


Figure 5. Examples of real events collected[35] with a small liquid Argon TPC prototype immersed in a magnetic field of 0.55 T: (left) bending of delta-ray (right) opening of an  $e^+e^-$  pair.

discrimination better than 1% with an efficiency of 20%[26]. Further studies are on-going.

An R&D program to investigate a LAr drift chamber in a magnetic field was started. In November 2004 the setup was finalized and first tests could be performed[35]. Following a cool-down phase of a few days, the chamber was filled up with liquid Argon and very clean cosmic ray tracks could be observed. After a few days of commissioning, the magnetic field was turned on and events collected with a liquid Argon TPC immersed in a magnetic field were collected (see Figure 5) demonstrating that it is possible to have a detector with the full bubble-chamber-like fine grain resolution provided by the liquid Argon imaging, with the additional possibility to measure particle momenta and the sign of electric charge via magnetic bending.

In order to fully address the oscillation processes at a neutrino factory, a detector should be capable of identifying and measuring all three charged lepton flavors produced in charged current interactions *and* of measuring their charges

to discriminate the incoming neutrino helicity. This would be the case with a magnetized liquid Argon TPC. From quantitative analyses of neutrino oscillation scenarios[27], one found that in many cases the discovery sensitivities and the measurements of the oscillation parameters were dominated by the ability to measure the muon charge. However, there were many cases where identification of electron and tau samples contributes significantly (see Refs. [26,27]). For example, it would open the possibility to measure the electron charge vital for the search for  $T$ -violation!

#### 4. NON-MAGNETIZED FINE-SAMPLING CALORIMETER

The NuMI neutrino beam line and the MINOS experiment[2] represent a major investment of US High Energy Physics in the area of neutrino physics. The forthcoming results could decisively establish neutrino oscillations as the underlying physics mechanism for the atmospheric  $\nu_\mu$  deficit and provide a precise measurement of the corresponding oscillation parameters,  $\Delta m_{32}^2$  and  $\sin^2 2\theta_{23}$ .

The full potential of the NuMI neutrino beam can be exploited by complementing the MINOS detector, under construction, with a new detector(s) placed at some off-axis position and collecting data in parallel with MINOS. The first phase of the proposed program includes a new detector, optimized for  $\nu_e$  detection, with a fiducial mass of the order of 50 kton and exposed to neutrino and antineutrino beams.

An off-axis NuMI neutrino beam offers an unique opportunity to study  $\nu_\mu \rightarrow \nu_e$  oscillations. There will be a very large number of  $\nu_\mu$ 's oscillating away. Most of the resulting  $\nu_\tau$ 's will be below the kinematical threshold for  $\tau$  production hence a small admixture of  $\nu_e$ 's should be detectable with as small background as possible.

To take full advantage of this opportunity it is necessary to construct a new detector capable of the detection and identification of the  $\nu_e$  charged current interactions. Such a detector must meet several challenges:

- it must have fine granularity in order to



identify the final state electrons

- it must have very large mass to provide maximal sensitivity to the oscillation amplitude
- it must have an acceptable cost per unit mass
- it must be able to operate on surface or under a small overburden, as there are no convenient underground locations

The detector should be optimized for the neutrino energy range of  $1 - 3 \text{ GeV}$ .

Identification of the final state electron in a calorimetric detector requires that the sampling frequency is high, of the order of  $1/4 - 1/3$  of the radiation length  $X_0$ . Neutrino detectors must serve as a target and as a detector at the same time, hence their mass must be maximized. These two requirements lead to a conclusion that the absorber should be made out of a low  $Z$  material to maximize the mass of the detector while maintaining good sampling frequency. Low  $Z$  absorber will lead to a minimal number of the active detector planes, for a given total mass of a detector, hence it will minimize the cost of the detector.

A required transverse granularity of the detector is related to the local particles density on one hand and to the Moliere radius on the other hand. Hadron and electron showers develop over large volumes in a low density detectors, hence the requirements on the transverse granularity of the detector will be relatively modest.

The NOvA collaboration[36] submitted a proposal to construct a 50 kton sampling detector built from particle board and liquid scintillator with APD readout. The detector would be located above ground, with a long baseline of about 800 km and an off-axis displacement of about 12 km from the main NUMI beamline.

Recently, the collaboration also presented the preliminary design of an attractive alternative detector based on a totally active liquid scintillator design (TASD). Simulations of this option showed an improvement in efficiency of almost a factor two. Like the baseline detector, TASD is a tracking calorimeter with alternating vertical

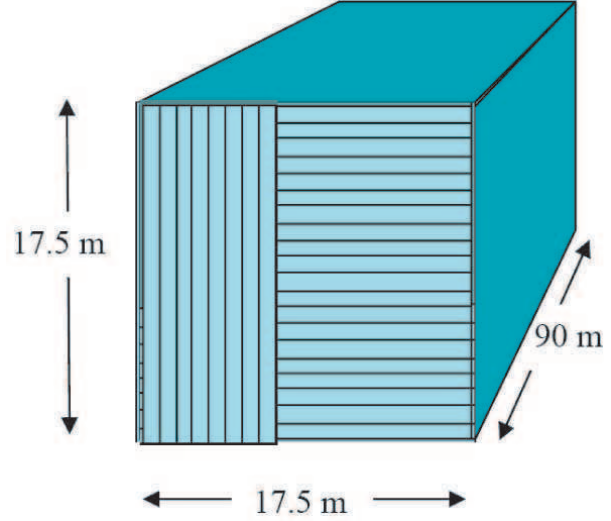


Figure 6. The proposed FNAL TASD detector composed of 17.5 m long PVC extrusions filled with liquid scintillator.

and horizontal planes of active liquid scintillator contained in PVC extrusions. Unlike the baseline design, there is no absorber, so TASD is expected to be 85% active and 15% PVC. The overall dimensions are 17.5 m (width)  $\times$  17.5 m (height)  $\times$  90.4 m (length).

The physics program offered by this design is rather limited and in direct competition with the approved T2K program. It is not yet clear how this design can evolve with potential future neutrino program beyond the NUMI program.

The technology is simple but requires volume instrumentation. Hence, the scaling properties beyond the currently proposed mass of 25 kton will be limited by the cost, unless the sampling rate is further reduced. The sampling rate can be optimized for a given physics application, as was performed in the NOvA proposal. This necessarily limits the discovery potential of this experiment beyond what has been foreseen at the level of the proposal. Given the size of this project (and the estimated detector cost of about 150 M\$ or about 3 times cheaper than MINOS per kton),

the window opportunity for this technology is rather limited and only sensible if timely completion with a similar timescale as T2K can be granted.

This kind of detector is not adequate for a Phase-II program.

## 5. MAGNETIZED SAMPLING CALORIMETER

The MINOS far detector[2] has a total mass of 5.4 kT. It is placed in a new cavern dug 713 m underground in the Soudan mine in northern Minnesota, about 735 km away from the primary target at Fermilab. The far detector is made out of two super-modules, each an 8m-diameter octagonal toroid composed of 243 layers. Each layer is made of a 2.54 cm-thick steel plane and 1 cm-thick and 4.1 cm-wide scintillator strips grouped in 20- or 28-strip wide light-tight modules. The scintillator strips are made in an industrial extrusion process using Styron 663W polystyrene, manufactured by the DOW chemical company, doped with 1% PPO and 0.03% POPOP. A 0.25 mm-thick reflective layer, made by adding 12.5%  $\text{TiO}_2$  to polystyrene, is co-extruded with the scintillator strips. A 1.4 mm-wide and 2 mm-deep groove in the center of the 4.1 cm-side is also made during the extrusion process. A 1.2 mm diameter wave length shifting (WLS) fiber is embedded in the groove during the assembly of the scintillator modules. The J-type Y11 multi-clad PMMA, non-S WLS fiber made by Kuraray and doped with the K27 dye at 175 ppm (with maximum intensity emission at 520 nm) is used. The fibers are optically coupled to the scintillator strips with epoxy. The WLS fibers are read out from both ends. They are grouped (multiplexed) inside a light-tight box into sets of 8 fibers from strips spaced more than 1 m apart in each plane. Each 8-fiber bundle is coupled, using a “cookie”, to a single pixel of a 16-pixel R5900-M16 Hamamatsu photomultiplier (PMT). Thus each PMT reads out 128 fibers; one end of each scintillator plane needs 24 pixels. This arrangement allows us to read out the entire MINOS far detector using only 1452 PMTs. Since the event rate is small, unambiguous event recon-

struction can be achieved in software despite the multiplexing. An important detector parameter is the photo-electron yield for a minimum ionizing particle (MIP) incident at right angle to the scintillator strip: the average yield, measured using a radioactive source for each strip during assembly, is about 6 photo-electrons per MIP summed from both sides. The attenuation over the 8 meter length of the strip is about a factor of 3. The detector is magnetized using a coil through a hole in the center of the planes to an average field of about 1.5 T (2 m away from the coil). The front end electronics is different for the two detectors because the event rate in the 8.1  $\mu$ -sec neutrino pulse in the near detector is far higher than the far detector. In the far detector the read out electronics is based on a VA chip from IDE and in the near detector it is based on the QIE chip designed at Fermilab. Simulations show that these detectors have a resolution of  $60\%/\sqrt{E}$  for hadronic showers and  $25\%/\sqrt{E}$  for electromagnetic showers. Both detectors are being calibrated by cosmic rays and a light injection system. A test beam calibration module is being used to perform relative calibration between the near and far detectors of about 2% and absolute calibration of about 5%.

The basic design of this kind of detector represents the old iron magnetized technology, with the drawback of volume instrumentation. Hence, scaling limited by the trade-off between the number of channels and the sampling rate.

This kind of detector has limited event reconstruction capability, and limited electron performance. For background estimation, one must heavily rely on Monte-Carlo estimates. It is mostly adequate for measuring deep-inelastic events and the leading muon charge. This detector is not adapted to low energy superbeam or betabeam and cannot address non-accelerator physics. It is most adequate for a neutrino factory, if one is only interested in wrong sign muons[37].

## 6. EMULSION-HYBRID

The basic performance of an OPERA-like detector at the Neutrino Factory in reconstructing

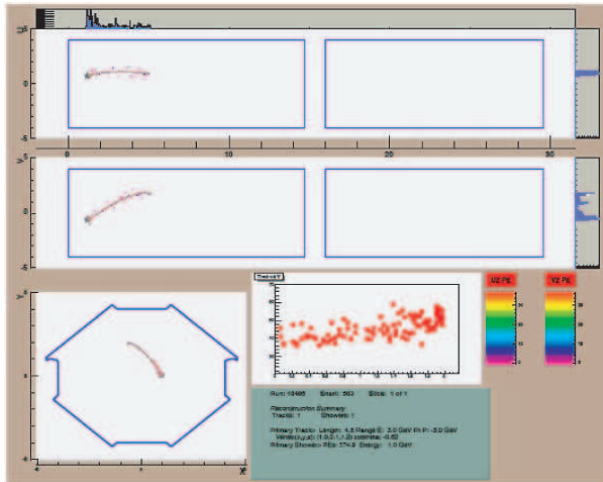


Figure 7. MINOS: one of the first candidate for contained neutrino interaction.

neutrino interactions was addressed in Ref.[38].

The experiment uses nuclear emulsions as high resolution tracking devices for the direct detection of the  $\tau$  produced in the  $\nu_\tau$  CC interactions with the target.

OPERA is designed starting from the Emulsion Cloud Chamber concept which combines the high precision tracking capabilities of nuclear emulsions and the large mass achievable by employing metal plates as a target. The basic element of the ECC is the cell which is made of a 1 mm thick lead plate followed by a thin emulsion film. The film is made up of a pair of emulsion layers 50  $\mu\text{m}$  thick on either side of a 200  $\mu\text{m}$  plastic base. Charged particles give two track segments in each emulsion film. The number of grain hits in about 50  $\mu\text{m}$  (15-20) ensures redundancy in the measurement of particle trajectories. By piling-up a series of cells in a sandwich-like structure bricks can be built, which constitute the detector element for the assembly of massive planar structures (walls). A wall and its related electronic tracker planes constitute a module. A supermodule is made of a target section, which is a sequence of modules, and of a downstream muon spectrometer. The detector consists of a sequence

of supermodules (see Fig. 8).

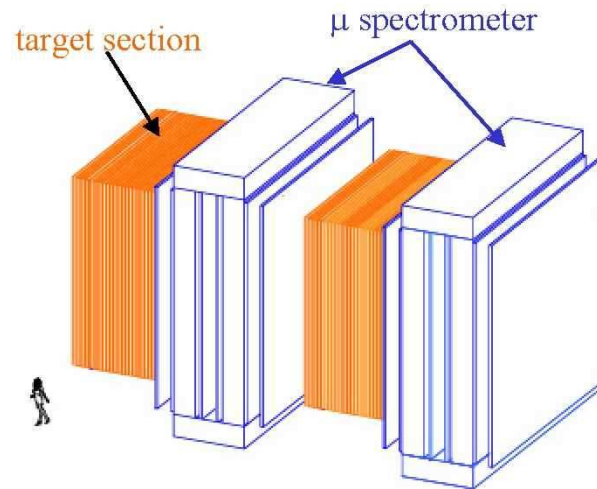


Figure 8. OPERA at CNGS.

The signal of the occurrence of a  $\nu_\tau$ CC interaction in the detector target is identified by the detection of the  $\tau$  lepton in the final state through the direct observation of its decay topology. A  $\tau$  may decay either into the lead plate where the interaction occurred (short decay) or further downstream (long decay). For long decays, the  $\tau$  is detected by measuring the angle between the charged decay daughter and the parent direction. The directions of the tracks before and after the kink are reconstructed in space by means of the pair of emulsion films sandwiching the lead plate where the interaction occurred. A fraction of the short decays is detectable by measuring a significant impact parameter (IP) of the daughter track with respect to the tracks originating from the primary vertex.

The detection of the  $\tau$  decay and the background reduction benefit from the dense brick structure given by the ECC, which allows the electron identification through its showering, the pion and muon separation by the  $dE/dx$  measurement method, and the determination of the mo-

mentum of each charged particle employing techniques based on the Multiple Coulomb Scattering. All these methods are discussed in the following.

Electronic detectors placed downstream of each emulsion brick wall are used to select the brick where the interaction took place (to be removed for the analysis) and to guide the emulsion scanning. The target electronic detectors are also used to sample the energy of hadronic showers and to reconstruct and identify penetrating tracks.

Overall, this detector is a hybrid between a sampling calorimeter and emulsions. Future application of this technology will be limited by its handling complexity and by the scanning load which is perceived as the bottle neck. The mass scaling is limited by cost of emulsions and event statistics is limited by emulsion scanning. It has an excellent long-lived track finding capability which is adequate for tau and charm identification. A possible physics program at a neutrino factory has been developed in Ref.[38].

## 7. CONCLUSION

From the considerations developed in this paper, we draw the following conclusions:

1. Not all technologies can satisfy the requirement of the general purpose and versatile detector, capable of simultaneously addressing non-accelerator and accelerator physics programs.
2. Only water Cerenkov detector and liquid Argon TPCs address in a satisfactory (and in fact in a complementary way, see e.g. Ref.[21]) solar, supernova, atmospheric neutrino and nucleon decay searches.
3. Superbeams and betabeams of subGeV and GeV energies can be coupled to water Cerenkov detector and liquid Argon TPCs. However, the high- $\gamma$  betabeam with energies above the GeV can only be efficiently coupled to a liquid Argon TPC, because Water Cerenkov are optimal for single ring events.
4. The neutrino factory necessarily requires magnetized detectors to measure the charge

of the leptons in order to discriminate between signal and background. A magnetized liquid Argon TPC or a non-magnetized liquid Argon TPC with an external muon spectrometer can be considered, aiming at identifying and measuring all three charged lepton flavors produced in charged current interactions and at measuring their charges to discriminate the incoming neutrino helicity.

5. Magnetized sampling calorimeters can be used at a neutrino factory for muon detection. Emulsion hybrid detectors can be in principle considered for tau detection, although serious handling issues may arise. These detectors cannot address the non-accelerator physics program.

The megaton Water Cerenkov detector may represent a conservative approach given the experimental knowledge gathered so far. However, the “100 kton liquid Argon” is certainly a challenging but potentially very performing design. Given the foreseeable timescale of more than a decade for the next generation of massive underground detectors, it is our conviction that a certain level of challenge represents the most attractive way towards potential progress in the field.

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